Experimentation, modeling and optimization of friction stir welding process for joining similar and dissimilar materials

A brief outline of the area of research proposed to be carried out in pursuance
for the award of the degree of

Doctor of Philosophy

in

Mechanical Engineering

Area of Research

Agile and intelligent manufacturing

Submitted by

Atul Suri

Supervisor

Prof. K. Hans Raj

Co- Supervisor

Dr. Rajat Setia

Research Scholar **Supervisor** **Co- Supervisor**

Head
Department of Mechanical Engineering

Dean
Faculty of Engineering

Faculty of Engineering,
Dayalbagh Educational Institute
(Deemed University)
Dayalbagh, Agra – 282005
(18th **September 2017**)

1.0 Introduction

Aluminum alloys find wide applications in aerospace, automobile industries, railway vehicles, bridges, offshore structure topsides and high speed ships due to its light weight higher strength to weight ratio and anti corrosive properties of some special alloys under extreme corrosive environment. In all cases, welding is the primary joining method which always represents a great challenge for designers and technologists. As a matter of fact, many difficulties are associated with this kind of joint process, mainly related to the presence of a tenacious oxide layer, high thermal conductivity, high thermal expansion coefficient, solidification shrinkage and, above all, high solubility of hydrogen, and other gases, in the molten state.

Friction Stir welding (FSW) has made revolutionary changes in the field of fabrication and proved to be in making various industrial parts. The process of Friction Stir Welding (FSW) was invented at The Welding Institute (TWI) of the United Kingdom in 1991 as a solid-state joining technique. Radically new joining processes do not come along very often: and since the inception of FSW research and development associated with this technology has mushroomed many industries to have more research in this area. Recently many reports on friction stir welding of various metal system such as aluminum, magnesium, mild steel, stainless steel, and dissimilar systems such as aluminum to stainless steel, aluminum to steel, aluminum to copper, aluminum to magnesium, have been published. Preliminary studies on the FSW or copper to copper and brass have also been reported. The process makes the use of a non- consumable rotating tool with specially designed pin/probe and the shoulder as shown in "Fig. 1". The rotating tool pin gets inserted in to the abutting edges of the plates to be joined and the tool is traversed along the weld line under the constant pressure on the shoulder to cause severe plastic deformation (SPD) and a permanent solid state joint.

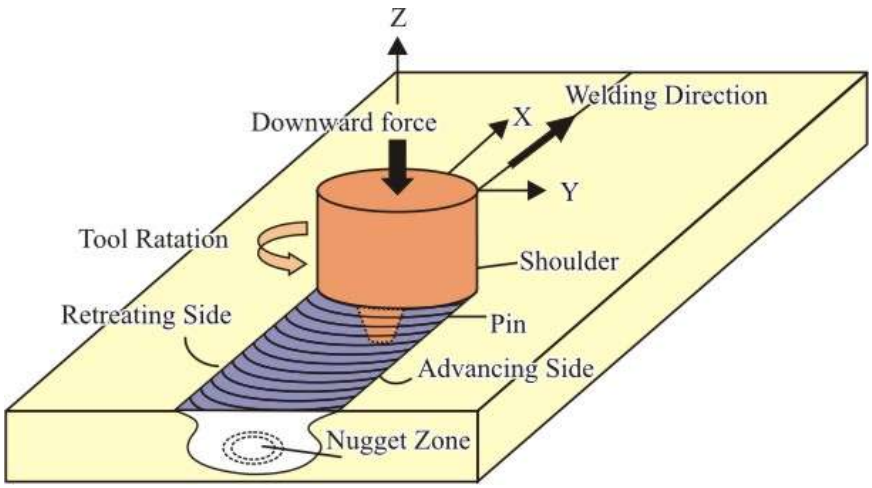

Figure 1:FSW principle of operation

The tool serves three primary functions, that is, heating of the work piece, movement of material around the pin to produce the joint, and containment of the hot metal beneath the tool shoulder. The diameter of the pin is generally considered as one third of the collar diameter and its length is slightly less than the thickness of the plate. The localized heating softens material around the pin and, combined with the tool rotation and translation, leads to movement of material from the front to the back of the pin, thus filling the hole in the tool wake as the tool moves forward. The tool shoulder restricts metal flow to the surface level position. Because of various geometrical features on the tool, material movement around the pin can be complex, with gradients in strain, temperature, and strain rate. During the joining process, FSW does not require shielding to prevent from the harmful gases. It is a safer and more economical method and does not require modes for eye protection and powerful ventilation to remove toxic gases.

In spite of the local microstructural in-homogeneity, one of the significant benefits of this solid-state welding technique is the fully recrystallized, equiaxed, fine grain microstructure created in the nugget by the intense plastic deformation at elevated temperature. The fine grain microstructure produces excellent mechanical properties, fatigue properties and enhanced formability and exceptional super plasticity. Tang et al. states that the temperature raised during FSW operation ranges from 70%-90% of the melting temperature of the work piece material. Colegrove et al. states that due to the increase in the temperature lesser than the melting temperature, the welding defects and large distortion commonly associated with the fusion welding are minimized. The heat is conducted to both tool and the work piece. The amount of heat conducted in to the work piece decides the quality of welded joint whereas the amount of heat transferred to the tool decides the tool life and quality of processed zone. Understanding above thermal requirements will help in improving the process to obtain better results.

FSW has been widely accepted as an upcoming process provides the ability to process selective locations on the structure's surface and to some considerable depth of about or more than an inch. FSW generates a fine, equiaxed grain morphology having a banded, bimodal grain size of 1-5 μm. Whereas microstructure resulting from FSW do not have a uniform grain size distribution for any given set of process parameters. Grain size varies from the top to the bottom as well as from the advancing to the retreating side. Since last decade many deformation processes are under investigation to obtain metals and alloys with ultrafine microstructures and consequently high strength. Hence, materials with nanometer or sub micrometer grain sizes are receiving greater interest because of their unique mechanical and physical properties and high performance. the strength of all polycrystalline materials is related to the grain size, d, through the Hall-Petch equation which states that the yield stress, σ_y is given by

$$\boldsymbol{\sigma_y = \sigma_o + k_y d^{-1/2}}$$

The production of materials with ultra fine grain sizes can be achieved by subjecting coarse grained metal to severe plastic deformation to improve their mechanical and physical properties. In case of FSW also the grain size in the weld zone is much dependent on various

parameters like tool geometry, tool rotational speed, too feed rate etc; and this influences the mechanical behavior of the weld joint.

1.1 Region of the weld zone

In FSW, new terms described below are necessary to adequately describe the post weld microstructures. The first attempt at classifying friction stir welded microstructure was made by Thread gill. Figure 2 identify the different microstructural zones existing after FSW, and a brief description of the different zones is presented.

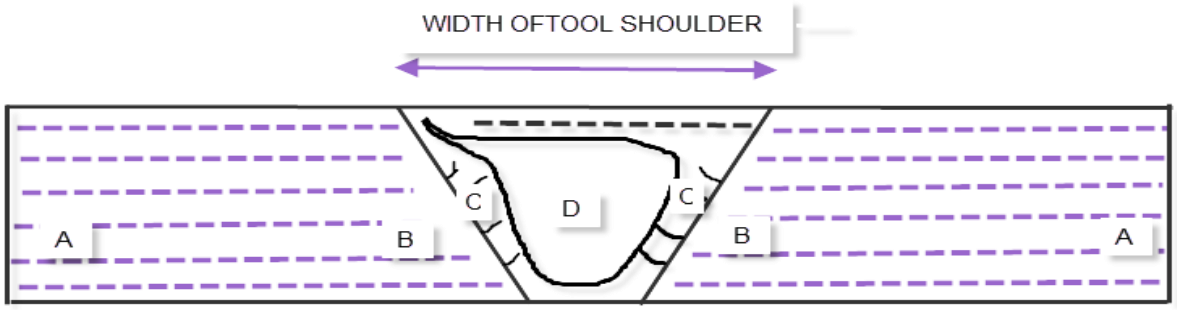

Figure 2: Different regions of weld zone

A systematic division of different weld zones into distinct regions is shown in fig. 2. Region A is material remote from the weld that has not been deformed and that, although it may have experienced a thermal cycle from the weld, is not affected by the heat in terms of microstructure or mechanical properties. Region B, which lies closer to the weld-center, the material has experienced a thermal cycle that has modified the microstructure and/or the mechanical properties. However, there is no plastic deformation occurring in this area.

Region C is thermo mechanically affected zone (TMAZ), the FSW tool has plastically deformed the material, and the heat from the process will also have exerted some influence on the material. In the case of aluminum, it is possible to obtain significant plastic strain without recrystallization in this region, and there is generally a distinct boundary between the recrystallized zone (weld nugget) and the deformed zones of the TMAZ. Weld nugget (D), is the fully recrystallized area, sometimes called the stir zone, refers to the zone previously occupied by the tool pin. The term stir zone is commonly used in friction stir processing, where large volumes of material is processed.

1.2 Benefits of FSW

We have discussed several benefits of Friction Stir Welding, and few of them we have already discussed. A consolidated list of benefits of FSW is discussed in Table: 1.

Table 1: Benefits of FSW

Metallurgical benefits	Environmental benefits	Energy benefits
• Solid- phase process • Low distortion • Good dimensional stability and repetability • No loss of allowing elements • Excellent mechanical properties • Fine recrystallized microstructure • Absence of solidification cracking • Welds all aluminum alloys	• No shielding gas required • Minimal surface cleaning required • Eliminate grinding waste • Savings of consumable materials ie. Rugs, wire and gases. • No harmful emissions	• Improved material use • Only 2.5% energy needed for laser welds • Decreased fuel consumption in light weight air craft, automotives and ship applications.

1.3 Tool material and design

Friction stirring is a thermo mechanical deformation process where the tool temperature approaches the work piece solidus temperature. Production of a quality friction stir weld requires the proper tool material selection for the desired application. All friction stir tools contain features designed for a specific function. Thus, it is undesirable to have a tool that loses dimensional stability, the designed features, or worse, fractures.

Selecting the correct tool material requires knowing which material characteristics are important for each friction stir application. Many different material characteristics could be considered important to friction stir, but ranking the material characteristics (from most to least important) will depend on the workpiece material, expected life of the tool, and the user's own experiences and preferences. In addition to the physical properties of a material, some practical considerations are included that may dictate the tool material selection.

- Ambient and Elevated Temperature Strength which is required to withstand the compressive and shear loads when the tool first makes contact with the work piece. Elevated Temperature Stability to maintain strength during the time of use. Creep (and creep fatigue) is a consideration for long weld lengths, where poor creep resistance would change the tool dimensions during welding.

- Wear Resistance as change in the tool shape changes the weld quality and increasing the probability of defects. Tool Reactivity with the workpiece or the environment would change (generally in a negative way) the surface properties of the tool. Titanium is well known to be reactive at elevated temperatures; thus, any reaction of titanium with the tool material will change the tool properties and alter the joint quality.

- Fracture Toughness plays a significant role during the tool plunge and dwell. The local stresses and strains produced when the tool first touches the workpiece are sufficient to break a tool, even when mitigation methods are used (pilot hole, slow plunge speed, and preheating of the workpiece).
- Coefficient of Thermal Expansion is a consideration in multi-material tools. Large differences in the coefficient of thermal expansion (CTE) between the pin and shoulder materials lead to either expansion of the shoulder relative to the pin or expansion of the pin relative to the shoulder. Both of these situations increase the stresses between the pin and shoulder, thus leading to tool failure. Machinability is important as design has no meaning if a tool material does not allow its processing to build that design

Further the design of the tool should be such that the pin of the tool should provide better stirring action of the material in the nugget zone with minimal contact so that heat associated defects can be avoided and the shoulder of the tool should provide superior friction on the job surface so that large amount of heat is generated beneath the tool shoulder.

1.4 Modeling and optimization

Selection of process parameters is an imperative and challenging task in any manufacturing environment, as that can give us optimum performance of machine and can lead us to quality products and good profits. The demanding problem of tradeoff between quality and cost is long standing challenge for which researchers are applying number of procedures and techniques. For any manufacturing system optimization is essential prerequisite. Therefore researcher have been using different modeling procedures that have been useful to represent the complete behavior of the system.

Evolutionary computation has become an important problem solving methodology among many researchers. The population based collective learning process, self adaptation and robustness are some of the key features of evolutionary algorithms when compared to other global optimization techniques. A population of candidate solutions (for the optimization task to be solved) is initialized. New solutions are created by applying reproduction operators (mutation and/or crossovers). The fitness (how good the solutions are) of the resulting solutions are evaluated based on the NN and NF models and suitable selection strategy is then applied to determine which solutions are to be maintained into the next generation. The procedure is then iterated to get the best solution.

The popular evolutionary algorithm that draws inspiritation from behavioral phenomenon of physical particle in nature is quantum inspired evolutionary algorithms (QIEAs). QIEAs are one of the three main research areas related to the complex interaction between quantum computing and evolutionary algorithms which are receiving renewed attention. QIEAs are the new class of nature inspired algorithms (NIAs) suitable for classical computer rather than for quantum mechanical hardware. Moore and Narayanan 1996 first attempted to exploit some of the principle of quantum mechanics, such as Q- bits,

superposition, quantum gates and quantum measurement, in order to solve various problems using a classical computer.

1.4.1 Optimization of process parameters of Friction Stir Welding process

It is intended to apply Quantum-inspired Evolutionary Algorithms (QIEA) in the proposed work as an optimization tool. The feasibility of these novel computational paradigms which are inspired by the principles of quantum mechanics, quantum bits and superposition of states (quantum parallelism) will be applied for optimizing Friction Stir Welding processes as intelligent manufacturing systems.

Quantum parallelism is a unique feature which turns out to be the key to the success of quantum algorithms. Like other evolutionary algorithms, QIEA is also characterized by the representation of the individual, the evaluation function and the population dynamics. However, instead of binary, numeric, or symbolic representation, QIEA uses a qubit, defined as the smallest unit of information, for the probabilistic representation and a qubit individual as a string of qubits. In this work it is proposed to use quantum-inspired evolutionary Algorithms for solving constrained optimization problems in Friction Stir Welding Processes. In such kind of manufacturing system the relation between various process variables is quite complex and is time dependent. Optimizing these processes is a very difficult task on account of various constraints. Often multiple conflicting objectives need to be achieved. QIEAs can be easily integrated with Neural Networks (NN) or Adaptive neuro fuzzy inference systems (ANFIS) for fitness estimation, which is expected to result in rapid convergence to better solutions even with multiple objectives.

1.4.2 Brief Introduction of QIEA

Quantum-inspired Evolutionary Algorithm (QIEA) is a kind of evolutionary algorithm where a qubit representation is adopted based on the concept and principles of quantum computation.

In conventional evolutionary algorithms encoding the solutions into chromosomes uses many different representations which can be generally grouped into three classes: symbolic, binary and numeric. In contrast, a QIEA uses novel probabilistic representation called qubit. Qubit is a smallest unit of information that can be in superposition of basis states in a quantum system. Qubits are generally represented by a vector in Hilbert space with $|0\rangle$ and $|1\rangle$ as basis states. The qubit can be represented as:

$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

where α and β are probability amplitudes of the qubit that may exist in state ‘0’ or in state ‘1’ so that it satisfies the normalization condition:

$$|\alpha|^2 + |\beta|^2 = 1$$

A qubit individual as a string of *m* qubits is defined as follows:

$$\left[\frac{\alpha_1}{\beta_1}\middle|\frac{\alpha_2}{\beta_2}\middle|\frac{....}{....}\middle|\frac{\alpha_m}{\beta_m}\right]$$

where $|\alpha_i|^2 + |\beta_i|^2 = 1,\ i = 1, 2, ..., m$

QIEA uses a better characteristic of diversity than classical approach since it can represent superposition of states. In classical bit string, a string of length *m* can represent 2^m possible states. However, a quantum space of *m* qubits has 2^m dimensions. Thus, a single qubit of length m can simultaneously represent all possible bit strings of length 2^m, for example, an eight qubit system can simultaneously encode 256 distinct strings. This implies that it is possible to modify standard evolutionary algorithms to work with very few, or even a single quantum individual, rather than having to use a large population of solutions encodings. The qubit representation can also help to maintain exploration and exploitation of entire search space due to its capability to represent multiple system states simultaneously. Convergence is also better achieved with such representation.

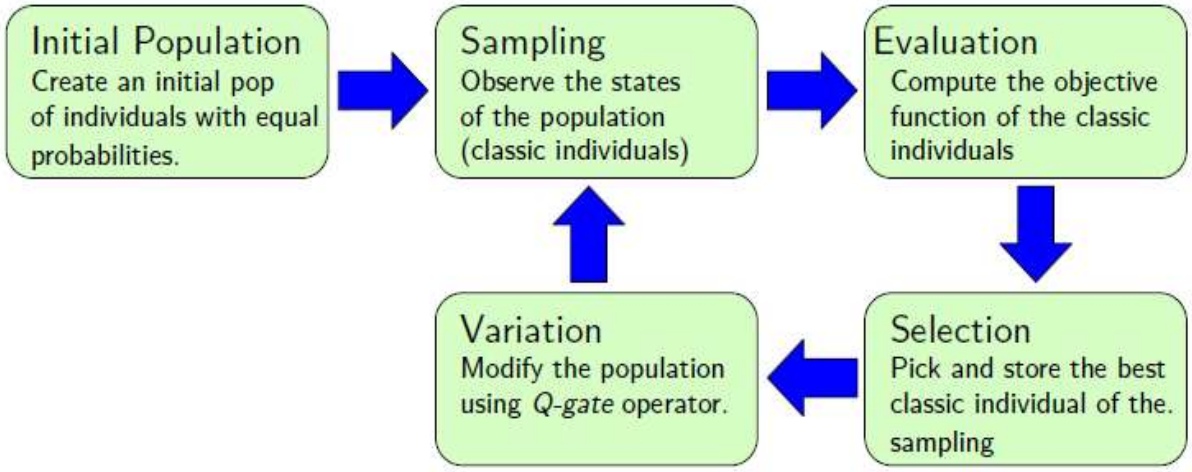
Initial Population
Create an initial pop of individuals with equal probabilities.
Sampling
Observe the states of the population (classic individuals)
Evaluation
Compute the objective function of the classic individuals
Selection
Pick and store the best classic individual of the. sampling
Variation
Modify the population using Q-gate operator.

Fig 3: Basic Flow chart of QIEA

1.4.3 Features of a Quantum-inspired Evolutionary Algorithms

There are several other inherent distinct advantages of quantum-inspired evolutionary algorithms. These apparent advantages over normal evolutionary algorithm are:

- Because of its probabilistic mechanism it possesses good global search ability and fast convergence to the best solution.
- Evolutionary computation with qubit representation has better characteristics of population diversity than other representations since it can represent linear superposition of states probabilistically.
- Because individuals in the quantum-inspired evolutionary algorithm are actually the superposition of multiple individuals, it is less likely that good individuals will be lost.
- Because the effective statistical size of the population appears to be increased, it improves the search process.
- Quantum-inspired evolutionary algorithms exhibit less computation time in comparison with other algorithms.

The power of these algorithms comes from the great diversity they provide by using quantum coding. Each single quantum individual in reality represents multiple classical individuals. The results reported from using this hybridization to solve combinatorial and continuous optimization problems are promising.

2.0 Review of Literature

Friction stir welding has opened up a new process for inducing directed, localized, and controlled materials properties in any arbitrary location and pattern to achieve revolutionary capability in high value-added components. Friction stir welding provides the ability to thermo-mechanically process selective locations on the structure's surface and to some considerable depth (>25 mm) to enhance specific properties. Research is being increasingly focused on this aspect of the technology for use with defense, naval, aerospace and automotive alloys. Microstructures resulting from FSW do not have a uniform grain size distribution for any one set of process parameters. Grain size varies from the top to the bottom as well as from the advancing to the retreating side. The ability of friction stir welding to change the local microstructure via thermo-mechanical working has been well established. The literature review and the patents in the field of severe plastic deformations and friction stir welding is discussed below.

2.1 Review on friction stir welding and severe plastic deformation

Sabirov et al. [Sab13] discussed new concepts and principles in application of SPD processing to fabricate bulk nano structured Al alloys with advanced properties. Many SPD techniques like equal channel angular pressing (ECAP) [Lan07], [Val11], [Sah12], high pressure torsion (HPT) [Zhi01], twist extrusion (TE) [Orl09], repetitive corrougation straightening (RCS) [23], friction stir processing (FSP) [Cha03], [Fad14], [Kar09], [Nad15], [Ela07], [Lan10] etc., have been developed and analyzed for producting bulk nano structured material [Kaw11], [Val05], Mos14] for the improved mechanical properties. Use of conventional Tungsten Inert Gas (TIG) and Metal Inert Gas (MIG) welding processes for joining aluminum melting can destroy the carefully engineered microstructures of composites thereby eliminating their unique properties. For aluminum plates in particular, welding issues such as oxidation, undesirable chemical reactions can cause weak welds that may contain porosity.

Lakshminarayanan et al. [Lak07] explains that conventional welds may become more susceptible to failures associated with the metallurgical changes that occur during localized melting. Thomas et al. [Tho91] and Dawes and Thomas [Daw96] states that, to address such limitations of conventional joining processes, Friction Stir Welding (FSW) is considered ever since its inception in 1991 at Welding Institute – TWI Cambridge.

Stephan et al. [Ste01] mention the application of this innovative welding process, attracted many researchers and is gaining wider industrial applicability. FSW is being applied in ship building, air craft manufacturing and automobile industries. Advantage of Friction stir welding as stated by Dawes and Thomas [Daw95] is that, it is dynamically continuous solid state joining process that has lower welding temperature, excellent weld-ability for similar and dissimilar aluminum alloys. Mohammed [Moh11] explains that in the FSW process, a special tool mounted on a rotating probe travels down through the length of the base metal plates in face-to-face contact. The tool serves three primary functions, that is, heating of the work piece, movement of material to produce the joint, and containment of the hot metal beneath the tool shoulder. Heating is created within the work piece both by friction between the rotating tool pin and shoulder and by severe plastic deformation of the work piece.

Thomas and Dolby [Tho03] explain that the probe of FSW tool is slightly shorter than the thickness of the work piece. The FSW joint is created by friction heating as well as severe plastic deformation due to the translation of the tool in the weld material. The stirring of the tool minimizes the risk of having excessive local amounts of inclusions, resulting in a homogenous and void-free weld. Since the amount of heat supplied is smaller than during fusion welding, heat distortions are reduced and thereby the amount of residual stresses. The deformation control is therefore easier. Karthikeyan and Balasubramanian [Kar10], explains that the microstructure in the stir zone is influenced by FSW parameters like tool geometry, tool rpm, shoulder penetration and feed rate which in turn influence the weld strength and ultimate tensile strength. Arora et al. [Aro10] reported that welding speed and shoulder

diameter effects tensile strength, and welding speed affects the joining efficiency and percentage of elongation of aluminum alloy 2219 in FSW.

According to an experimental work carried out by Bitondo et al. [Bit11], rolled plates of AA 2198 T3 aluminum alloy are used for FSW varying two important process parameters: rotational and welding speed. However there is a need to enhance the weld characteristics of the FSW joint, Therefore in this work an effort is made to use different tool geometries for welding of Al5083 plates and finding out best geometry and parameter for superior weld characteristics. Garware et al. [Gar10] studied the tailor welded blanks of aluminum alloy and studied the various mechanical properties like static –tensile and tension- fatigue behavior. It was observed that the yield and tensile strength of FSW specimen with weld located 90^0 to the tensile direction are close to the base material value, but its elongation is nearly half of the elongation of the base metal. Good tensile- fatigue properties were observed, and were even superior to the base metal.

Tansel et al. [Ten09] have performed butt welding of Al 1080 using FSW. The specimens were prepared and examined under tensile test. The ultimate strength of the specimen was found to of the order of about 50% of the base metal. The fracture is expected to take place at the weak weld zone. Five BP type ANNs were trained to represent the FSW operation. The estimation of ANNs were compared with the actual test results by using 3-D graphs. Prasanna et al. [Pra10] have attempted to determine the maximum temperature during FSW by varying the input parameter using ANSYS. The objective of the research was to develop a FE simulation with improved capability to predict temperature evolution in stainless steel. The results were observed to be in good agreement with the experimental results.

Shigematsu et al. [Shi09] have studied the dissimilar FSW tailor welded blanks of AL-Mg alloys. Spindle rotation was varied from 800 to 1400rpm with variable feed rate ranging from 100mm/min to 500mm/min. Average tensile strength was found to about 72% of the base metal where as elongation was about 2% or less comparing to base metal.

Chao et al. [Cha03] investigated the variations of heat energy and temperature produced by the FSW in both the workpiece and the pin tool. All investigations showed that the FSW of Aluminum alloys yielded welds with low distortion, high quality, and low cost. Consequently, better structural performance was the primary advantage of this technology's applications. In the model developed by Chao and Qi, the heat generation came from the assumption of sliding friction, where Coulomb's law was used to estimate the shear or friction force at the interface. Furthermore, the pressure at the tool interface was assumed to be constant, thereby enabling a radially dependent surface heat flux distribution as a representation of the friction heat generated by the tool shoulder, but neglecting that generated by the probe surface.

Frigaard et al. [Fri01] developed a process model for FSW, the heat input from the tool shoulder was assumed to be the frictional heat. The coefficient of friction was

continuously adjusted to keep the calculated temperature from exceeding the material melting point. In principle, the FSW process could be applied to join other alloy materials such as Steels and Titanium. But, it is well known that current tool materials used in the FSW for Aluminum are not adequate for production applications in many of the harder alloy materials. However, when adequate wear resistant tool materials become available, the benefits of the FSW may promote its rapid implementation in the production of ferrous structures and structures made from other refractory materials.

Reynolds et al. [Rey03] investigated the microstructures, residual stresses, and strength of the friction stir welds through experimental studies of austenitic stainless steels, and also stated that to improve the welding quality for the FSW of steels, numerical modeling, and simulations of transient temperature and residual stresses are valuable and necessary. Colegrove [Col00] used an advanced analytical estimation of the heat generation for tools with a threaded probe to estimate the heat generation distribution. The fraction of heat generated by the probe is estimated to be as high as Schematic of friction stir welding, which leads to the conclusion that the analytical estimated probe heat generation contribution is not negligible.

Sidhar et al. [Sid16] discusses about the Friction stir welding of 1424 Al–Mg–Li alloy using tool rotation rate of 800 rpm and traverse speed of 305 mm per minute. The temperature at the tool center was recorded for each weld and after post weld heat treatment, full recovery of strength was observed in the heat affect zone and the weld nugget. High joint efficiency of 97% of the base material was achieved. They also concluded that the homogenous and high density of Al3Li precipitation was reasoned for high strength joints.

Aval [Ava15] studied the effect of welding heat input and post weld natural aging on residual stress, microstructure, and precipitation distribution in different zones of dissimilar friction stir welding of 8 mm thick plates of AA6082-T6 and AA7075-T6. They concluded that atomic diffusion occurs at the interface of the materials in the stir zone of the joints. Transmission electron microscopic investigations showed that reprecipitation of fine Guinier–Preston zone, β', and η' precipitates resulted in increased micro-hardness in the SZ after natural aging. An increase in welding heat input resulted in decreased maximum tensile residual stress and increased size of the tensile residual stress region.

Feistauer et al. [Fei14] discusses the mechanical properties of dissimilar friction stir welded, tailor welded blanks (TWB). The joints were manufactured with dissimilar Al–Mg alloys and thicknesses (6 and 8 mm) of particular interest to the shipbuilding sector (AA5083 and AA5059). Microhardness and DIC analyses showed that the stir zone of the TWB presented overmatching in relation to the weakest base material, and that the joints displayed excellent overall mechanical performance that was comparable to the AA5059 base material in terms of strength and ductility. The fatigue strength was evaluated by means of tension–tension fatigue tests, and the TWB joints reached the fatigue keen with a stress range of 70 MPa.

Giraud et al. [Gir16] investigated friction stir welding of dissimilar heat treatable aluminum alloys 7020-T651 and 6060-T6. They attempted an experimental analysis based on results obtained from temperatures and efforts measurements in a range of advance speed from 300 to 1100 mm min−1 and rotation speed from 1000 to 2000 rev min−1. The material mixing of dissimilar configurations has been investigated by means of macro and microstructural observations and has revealed the complex mechanisms of material flow into the nugget. On the basis of tensile tests and microhardness characterizations they were able to determine a large window of industrial parameters capable of welding properly two 5 mm sheets of AA7020-T651 and AA6060-T6 with good mechanical properties.

Tongne et al. [Ton17] investigated AA6082-T6 friction welded joints using a triangle shape pin. The influence of Friction Stir Welding (FSW) process parameters on the formation of banded structures was predicted using numerical modeling and then experimentally validated by optical and electron microscopy. They developed finite element (FE) analysis based on the Coupled Eulerian– Lagrangian formulation to predict and quantify the influence of FSW process parameters on the formation and extent of the banded structures.

Imam et al. [Ima16] discussed the parameters controlling the structure-properties relationships both across weld cross-section and through thickness direction through mechanical testing, electron backscatter diffraction technique, transmission electron microscopy, and occurrence of serrated plastic flow. They concluded that the evolution of the properties in the weld cross-section showed that the presence of un-dissolved and fragmented Al6MnFe particles which cause discrepancies in establishing the Hall-Petch relationship, and derive the strengthening from the Orowan strengthening mechanism.

Aktarer et al. [Akt15] discusses the effect of two pass friction stir processing (FSP) on microstructural evolution, mechanical properties and impact toughness of as cast Al-12Si alloy. The hardness, strength, ductility and impact toughness of the alloy increases simultaneously after two pass FSP. The increase in the yield strength value after FSP was about 20% and corresponding tensile strength increases by 29% of the base metal. The FSPed alloy exhibited 25% elongation to failure and 15% uniform elongation which were almost seven times and six times respectively than those of as cast alloy.

Malard et al. [Mal15] studied the distribution of precipitate microstructures which is mapped in the cross-section of a friction stir weld made with an AA2050 Al–Cu–Li alloy in the naturally aged temper, as well as the evolution of this microstructure during subsequent post-welding heat treatment (PWHT). They carried out the study using spatially resolved small-angle X-ray scattering, supported by transmission electron microscopy, differential scanning calorimetry and microhardness mapping. They investigated that the as-welded microstructure is dominated by solute clusters, while very little precipitation has taken place during the welding operation. During PWHT, the precipitation kinetics in the different zones of the weld is mainly controlled by the local dislocation density inherited from welding, and by the amount of solute available for precipitation, which depends on the volume fraction of welding-induced intermetallics. Hence, they concluded pre-deforming the weld before the

PWHT results in a very effective strength recovery and a nearly homogeneous distribution of hardness.

2.2 Reviews on modeling and optimization of friction stir welding & SPD

Ghaffarpour et al. [Gha13] used the design of experiments (DOE), the Box–Benken method, and the response surface methodology (RSM) were used to optimize the effective parameters of the FSW process for the dissimilar aluminum alloys of 5083-H12 and 6061-T6. The optimized parameters that led to the maximum tensile strength in dissimilar friction stir welded sheets were determined and the predicted results were then compared with those measured experimentally. Further, they also applied the limit dome height (LDH) test for the formability of friction stir welded sheets. During the LDH test, the minimum formability occurred in the heat-affected zone (HAZ) of the 6061-T6 side.

K. Hans Raj et al. [Han04] demonstrated the effectiveness of the hybrid approach formulated by integrating finite element (FE) models, artificial neural networks (ANN), genetic algorithms (GA) and simulated annealing (SA) in process optimization for hot closed die forging of an automotive piston. Two ANN models are developed which determines the maximum equivalent strain rate and the final forging load for a given set of input process parameters i.e. punch velocity, billet temperature and friction coefficient. Further, a multi-objective neuro hybrid stochastic search technique (MONHSST) is developed by integrating GA and SA with ANN models for finding the optimal process parameters.

K Hans Raj et al. [Han07] developed a generic approach where the applicability and effectiveness of Neuro-Fuzzy model for functional approximation is used to rapidly estimate cutting forces in machining in an integrated framework of Hybrid Stochastic Search (HSS) algorithm to form a Neuro-Fuzzy Hybrid Stochastic Search Technique (NFHSST). The results indicate that the NFHSST heuristic converges to better solutions rapidly as it provides the values of various process parameters for optimizing the objectives in single run. The results of NFHSST are validated with optimization results obtained by analysis of mean of orthogonal arrays.

Grosan et al. [Gro07] illustrated the various possibilities for hybridization of an evolutionary algorithm and also presented some of the generic hybrid evolutionary architectures that has evolved during last couple of decades. Evolutionary algorithm behavior is determined by the exploitation and exploration relationship kept throughout the run. K Hans Raj et al. [Han09] developed a Neuro-Fuzzy technique to predict the punch force required to extrude a transmission shaft from ck-45 billet steel. This work has considerable implications in selection and control process variables in real time and ability to achieve energy and material savings, quality improvement and development of homogeneous properties throughout the component. This technique opens up new avenues of parameter estimation, optimization and on-line control of complex agile manufacturing systems.

Prasanth et al. [Pra17] have studied the Friction Stir Welding of Dissimilar alloy of aluminum (AA6351- T6 and AA6061- T6) using three factor and five level central composite

rotatable design method. Empirical relationship was developed between input parameters and response variables such as ultimate strength, yield strength, and percentage elongation and are estimated using analysis of variance techniques. Artificial bee colony algorthims were also applied to get the optimal parameters to achieve good mechanical properties of FS weld joints. R Karthikeyan and V. Balasubramaninia [Kar10] have studied FSW parameters such as rotational speed of the tool, penetration rate, plunge depth and the dwell time of the tool and their effect on the goodness of the weld. A model was developed to predict the shear fracture load for the spot welded joint of AA 2024 alloy of aluminum by incorporating FSW parameters. Response surface methodology (RSM) was applied to optimize spot welding parameter to attain maximum strength of the joint.

Bitondo et al. [Bit11] have analyzed FSW of AA2198-T3 alloy on two parameters i.e. rotational speed and feed rate of the tool. Empirical model based on regression analysis was developed for tool force and mechanical strength. Confidence level of model accuracy was found to be about 95%. C N Suresha et al. [Sur11] analyzed the FSW to AA7075-T6 and Taguchi method was used for the model development and its optimization. Percentage contribution of each parameter on tensile strength of FSW joint was analyzed. Dinaharan et al. [Din12] used ceramic particles which were added to aluminum and used to produce aluminum matrix composites. In attempt of performing friction stir welding of AA6061/ ZrB2 a mathematical model was developed which predicts the tensile strength of the joint based on input parameters. It was stated that change in any input parameter would cause a change in the ultimate tensile strength over the complete range.

Blignault et al. [Bli12] considered different tool geometries of FSW tools and developed a model. Statistical analysis of the data was performed to find out the influence of different combinations of process parameters and tool geometries on tensile strength. Using their model they predicted the strength for unknown parameters and tool geometries and the model depicts an accuracy of about 87 percent.

Ghetiya et al. [Ghe16] attempted analysis of variance was used to study significance of process variables on grey relational grade which showed rotational speed and welding speed to be most significant parameters. Other than rotational speed and welding speed, tool shoulder diameter and axial load were also found to be significant. To validate the study, confirmation experiments were carried out at optimum set of parameters and predicted results were found to be in good agreement with experimental findings.

Naghibi et al. [Nag16] attempted to find optimal parameter setting of tool rotary speed, welding speed and tool offset regarding maximum tensile strength and elongation for AA 5052 and AISI 304 dissimilar joints. For this purpose, firstly an intelligent correlation between mentioned factors and tensile properties was developed by using neural network. Then, the developed network was integrated with genetic algorithm to find optimal solutions to achieve desirable mechanical properties. The obtained result is verified by conducting confirmatory experiment.

Silva et al. [Sil15] set of optimization studies for different friction stir welding joint geometries of AA6082-T6 aluminum alloy: butt, lap and T joints. The optimization process was performed using Taguchi orthogonal arrays (OA) for designing experiments, analyses of the average effects (main effect plot) and variance (ANOVA). Welded joints were manufactured according to orthogonal arrays, selected using the Taguchi method, for each type of joint, and the ultimate tensile strength (UTS) was evaluated for statistical optimization.

Aliha et al. [Ali16] attempted friction stir welding process of dissimilar AA6061-T6 and AA-7277-T6 aluminum plates. Using artificial neural network (ANN) approach, the hardness and ultimate tensile strength of tested AA6061-T6 and AA-7277-T6 aluminum joint was predicted for different friction stir welding (FSW) process variables including the pin speeds and material position on advancing side (AS) and (RS). Also, using a multi-objective optimization technique, a Pareto front (or Pareto optimal set) was obtained for both hardness and tensile strength results.

Shojaeefard et al. [sho14] studied the influence of rotational and traverse speed on the friction stir welding of AA5083 aluminum alloy has been investigated. For this purpose a thermo-mechanically coupled, 3D FEM analysis was used to study the effect of rotational and traverse speed on welding force, peak temperature and heat affected zone (HAZ) width. Then, an artificial neural network (ANN) model was employed to understand the correlation between the welding parameters (rotational and traverse speed) and peak temperature, HAZ width and welding force values in the weld zone. Performance of the ANN model was found excellent and the model can be used to predict peak temperature, HAZ width and welding force. Furthermore, in order to find optimum values of traverse and rotational speed, the multi-objective optimization was used to obtain the Pareto front.

Kamal Babu et al. [Kam17] performed parameter optimization of FSW of cryorolled AA2219 alloy was carried out to obtain defect free weld joint with maximum weld strength. To achieve this, artificial neural network (ANN) was used to model the relationship between the input parameters and the mechanical and corrosion properties (output) of the weld joints. The optimal FSW parameters were determined by genetic algorithm (GA). The feasible solution of the GA was tool rotational speed of 1005 rpm, tool travel speed of 20 mm/min and tool tilt angle of 3°.

3.0 Statement of the problem

In the present scenario of manufacturing it is required to maintain the balance between the quality and cost of the product. For which selection of design parameters and process parameters plays a significant role. In the present research there will be an emphasis on designing some tools with geometries that can perform better in terms of gaining superior quality of the weld as a result from better stirring action and minimal contact in the nugget zone for minimizing heat associated defects, which are often produced at low translation rate of the tool and high rotational speed of FSW tool. Apart of this there can be some other new experimentation work which can improve the goodness are listed below:

- Every researcher has used Vertical axis of the tool for performing FSW where as a horizontal axis can also be considered using a conventional/ CNC lathe machine that is far cheaper than vertical axis milling machine and possess the additional advantage of space and time saving and providing easy tool maintenance (without changing the machine) to clear the seized material on the tool pin.

- In the exhaustive survey it was found that ultimate strength of the welded joint (Aluminum- Aluminum) is of the order of 75% of the base metal using single sided FSW. In the present work an attempt will be made to increase the strength of the joint by a large extent in order to provide better factor of safety of the joint. This will be accomplished by a new process named as reinforced friction stir welding (RFSW), and the results obtained by this will be compared by conventional method.

- Strength of the welded joint is also dependent on the area of contact of the abutting plates. In this research attempt will be made for increasing the contact area of the abutting surfaces for the same thickness by providing taper on the contact surfaces, which may improve the joint efficiency.

Once the experimental work is performed by selecting the process parameters manually, it is important to find the best input parameters so as to produce best output in terms of goodness of weld. Manual selection is quite ineffective in the agile manufacturing environment and deterministic approaches make the computation laborious, complex and often fail to get global optimal solution. Complexity due to non linearity of processes makes selection of parameters further more difficult. Here hybrid evolutionary algorithms/ ANFIS and quantum inspired evolutionary algorithms (QIEA) are quite useful and often used for solving real world optimization problems.

The frame work of the proposed research is to develop a model in NN/ ANFIS/ RSM techniques for training purpose using data set obtained experimentally and testing the model for unknown process parameter and validating the same experimentally. This model will act as a fitness evaluator for optimization of the FSW process. After developing and validating the model for FSW, optimization of the model will be performed using quantum inspired evolutionary algorithms.

4.0 Objectives of the proposed research

1. To perform FSW on similar and dissimilar alloys of Aluminum (Al 5xxx and Al 6xxx series) using new tools using computerized vertical milling machine (VMC) at different process parameters such as tool rpm, feed rate, annealing temperature and different tool geometries.

2. To measure the output response using experimental analysis of the welded joint in terms of ultimate strength, yield strength, hardness, toughness and izod impact value and grain size in the nugget zone.

3. To apply soft computing techniques and making a model of FSW process for joining aluminum alloys using ANN/ANFIS/RSM for training and validation purpose. After validation of the model Quantum inspired evolutionary algorithms (QIEA) will be used for the optimization of FSW model and the optimized results obtained will be validated using experimental test.

4. An attempt will be made to produce an accessory to perform FSW on lathe machine in order to save cost, space and maintenance time of FSW tool. After performing FSW using horizontal tool axis (HTA) on conventional lathe machine the results will be compared with the results of VMC on optimal parameters obtained by QIEA.

5. Performing a new conceptual process of reinforced friction stir welding (RFSW) on optimal parameters obtained by QIEA and comparing the mechanical behavior with above two schemes.

6. Performing FSW on optimal parameters by increasing the contact area of the abutting surface for the same thickness by providing taper on the contact surfaces and testing the same for mechanical behavior and comparison with above schemes.

7. Drawing conclusion to the above work to find advantage and disadvantage of the specific scheme.

4.0 Methodology

It has been observed on the basis of above mentioned reviews that in order to achieve advanced mechanical properties of FSW joints of dissimilar Aluminum plates, it is extremely necessary to control a wide range of fundamental parameters and experimental factors. In the present work, we will be giving due importance to the tool Shoulder Diameter (TSD), Tool Pin Geometry (TPG), Tool Rotational Speed (TRS), Tool Feed rate (TFR) and effect of Pre & Post Annealing of the work pieces on the goodness of the weld, mechanical strength and microstructure of the welded joint. Joining of specimen of similar and dissimilar aluminum alloys will be studied in this work. Methodology is described in following stages:

Stage 1: *includes FSW on vertical milling machine using conventional technique and newly developed tool. Following are the steps:*

1. Selection of two different alloys of aluminum. The first alloy that is considered for the study is Al 5083 that is known for exceptional performance under extreme environment. It is highly resistant to attack by sea water and industrial chemicals. Other alloy is taken as Al 6063 which is very good for architectural and fabrication work.
2. Developing new tools and a conventional tool to perform FSW.
3. Performing FSW on similar and dissimilar plates using parameters listed above.
4. Measurement of output response using experimental analysis of the welded joint in terms of ultimate strength, yield strength, hardness, toughness and izod impact value and grain size in the nugget zone.
5. Developing a model using experimentally generated data by soft computing techniques viz. ANN/ANFIS/RSM models.
6. Validation of the model on unknown input parameter.
7. Optimization of FSW model using QIEA/ Soft computing.
8. Validation of results of QIEA experimentally.

Stage 2: *Includes invigorated work to be trial and tested for better performance than conventional method. Following are the steps:*

9. Development of a new accessory for lathe and performing FSW using horizontal tool axis (HTA) on lathe machine on optimized parameters and comparing results with optimized (QIEA generated) output.
10. Performing FSW after increasing contact area of the abutting surfaces for the same thickness using opposite taper on the butt contact surfaces on optimized parameters and comparing the results with optimized output.
11. Performing FSW using extra reinforcement strip over the abutting surface for excellent strength of the joint and comparing the same on optimized parameters. The process is named as reinforced FSW (RFSW).
12. Drawing out conclusion of the whole research.

References:

[Akt15] S. M. Aktarer, D. M. Sekban, O. Saray, T. Kucukomeroglu, Z. Y. Ma, G. Purucek, "Effect of two pass friction stir processing on the microstructure and mechanical properties of as cast binary Al-12Si alloy", *Material Science & Engineering* A, 636, **2015**, pp. 311-319.

[Ali16] M. R. M Aliha, M. shahheidari, M. Bisadi, M. Akbari, S. Hossain, "Mechanical and metallurgical properties of dissimilar AA6061-T6 and AA7277-T6 joint made by FSW technique", *Int J Adv Manuf Technol*, vol 86, **2016**, pp.2551-2565.

[Aro10] K. S. Arora, S. Pandey, M. Schaper, R. Kumar, "Effect of process parameters on friction stir welding of aluminum alloy 2219-T87", *Int J Adv Manuf. Technol.*, 50, **2010**, pp. 941–952.

[Ava15] H. J. Aval, "Microstructure and residual stress distributions in friction stir welding of dissimilar aluminium alloys", *Materials and Design*, 87, **2015**, pp. 405-413.

[Bit11] C. Bitondo, U. Prisco, A. Squilace, P. Buonadonna, G. Dionoro, "Friction-stir welding of AA 2198 butt joints: mechanical characterization of the process and of the welds through DOE analysis", *Int J Adv Manuf Technol*, 53, **2011**, pp. 505–516.

[Bit11] C. Bitondo, U Prisco, A. Squilace, P. Buonadonna, G. Dionoro, "Friction stir welding of AA2198 butt joints: mechanical characterization of the process and of welds through DOE analysis", *Int J Adv Manuf Technol*, vol 10, **2011**, pp. 2879-9.

[Bli12] C. Blignault, D. G. Hattingh, M. N. James, "Artificial bee colony algorthim for large scaleproblems, and engineering design optimization", *JMEPEG*, vol 21, **2012**, pp. 927-935.

[Cha03] I. Charit, R. S. Mishra, "High strain rate superplasticity in a commercial 2024 Al alloy via friction stir processing", *Mater Sci Eng* A, 359, **2003**, pp. 290–296.

[Cha03] Y. J. Chao, X. Qi, W. Tang, "Heat Transfer in Friction Stir Welding-Experimental and Numerical Studies", *Journal ASME Journal of Manufacturing Science Engineering*, 25, **2003**, pp.138-145.

[Col00] P. Colegrove, M. Painter, D. Graham, T. Miller, "Dimensional flow and thermal modelling of the friction stir welding process", *Proceedings of the Second International Symposium on Friction Stir Welding*, June 26-28, Gothenburg, Sweden, **2000.**

[Daw95] C. Dawes, W. M. Thomas, "Friction stir joining of aluminum alloys", *TWI Bulletin*, **1995.**

[Daw96] C.J. Dawes, W. M. Thomas, "Friction stir process welds aluminum alloys", *Welding Journal* 75(3), **1996**, pp. 41 – 45.

[Din12] I. Dinaharan, N. Murugan.: "Optimization of friction stir welding process to maximize tensile strength of AA6061/ ZrB2 In- Situ composite butt joint", *Met. Mater. Int.*, 1(18), **2012**, pp. 135-142.

[Ela07] K. Elangovan, V. Balasubramanian, "Influences of pin profile and rotational speed of the tool in the formation of friction stir processing zone in AA2219 aluminum alloy", *Mater Sci Eng*, A459, **2007**, pp. 7–18.

[Fad14] K. J. Al Fadhalah, A.I. Almazrouee, A.S. Aloraier, "Microsturcture and mechanical properties of multi pass friction stir processed aluminim alloy 6063", *Materials and Design*, 53, **2014**, pp. 550-560

[Fei14] E. E. Feistauer, L. A. Bergmann, L. S. Barreto, J. F. Dos Sentos, "Mechanical behavior of dissimilar friction stir welded tailor welded blanks in Al-Mg alloys AA5083/AA5089) for marine applications", *Materials and Design*, 59, **2014**, pp.

323-332.

[Fri01] G. Frigaard, O. T. Midling, "A Process Model for Friction Stir Welding of age hardening aluminium alloys", *Metallurgical and Materials Transactions,* 32A(5), **2001**, pp. 1189-2000.

[Gar10] M. Garware, G. T. Kridli, P. K. Mallick, ,"Tensile and Fatigue Behavior of Friction-Stir Welded Tailor-Welded Blank of Aluminum Alloy 5754", *Journal of Materials Engineering and Performance*, 19(8), **2010**, pp.1161-1171.

[Gha13] M. Ghaffapour, S. Kolahgar, B. M. Dariani, K. Dehghani, "Evaluation of dissimilar welds of 5083-H12 and 6061-T6 produced by friction stir welding", *Metallurgical and Material Transactions A*, 8(44), **2013**, pp 3697-3707.

[Ghe16] N. D Ghetiya, K. M Patel, A. J Kavar, "Multi-objective Optimization of FSW Process Parameters of Aluminium Alloy Using Taguchi-Based Grey Relational Analysis", *Trans Ind Inst Met*, vol 69(4), **2016**, pp. 917-923.

[Gir16] L. Giraud, H. Robe, C. Claudin, C. Desrayaud, P. Bocher E. Feulvarch, "Investigation into dissimilar friction stir welding of AA7020-T651 and AA6060-T6". *Journal of Material Processing Technology*, 235, **2016**, pp. 220-230.

[Gro07] C. Grosan and A. Abraham, "Hybrid evolutionary algorithms: Methologies, Architectures and Reviews", *Studies in Computational Intelligence*, **2007**, pp. 1-17.

[Han04] K. HansRaj, S. Srivastava, K. Srivastava and R. S. Sharma, "Multi-Objective process optimization of hot closed die forging for intelligent Manufacturing", *International Journal of Agile Manufacturing*, 7,(2), **2004**.

[Han07] K. HansRaj, R. S. Sharma, V. Upadhyay and A. K. Verma, "Modeling and Optimization of Turning Process", *International Journal of Agile Manufacturing*, vol. 9 (1), **2007**.

[Han09] K. HansRaj, Rahul Swarup Sharma and Vikas Upadhyay, "Neuro-Fuzzy modeling of hot extrusion process", *Indian Journal of Engineering and Materials Sciences*, vol. 16, **2009**, pp. 86-92.

[Hua01] J. Huang, Y. T. Zhu, H. Zhiang, X. Liao, T.C. Lowe, "Microstructures and Dislocation configuration in nanostructured Cu processed by repetitive corrugation and straightening", *Acta Mater*. 49, **2001**, pp. 1497-1505.

[Ima16] M. Imam, Y. Sun, H. Fuji, N. Ma, S. Tsutsumi, H. Murukawa, "Microstructure characteristics and mechanical properties of friction stir welded thick 5083 aluminium alloy", *Metallurgical and Material Transactions*, A, **2016**, pp 1-22.

[Kam17] K. Kamal Babu, K. Panneerselvam, P. Sathiya, A. Noorul Haq, S. Sundarrajan, P. Mastanaiah, C. V. Srinivasa Murthy, "Parameter optimization of friction stir welding of cryorolled AA2219 alloy using artificial neural network modeling with genetic algorithm", *Int J Adv Manuf Technol*, **2017**, DOI 10.1007/s00170-017-0897-6.

[Kar09] L. Karthikeyan, V.S. Senthilkumar, V. Balasubramanian, S. Natrajan, "Mechanical property and microstructural changes during friction stir processign of cast aluminium Al 2285 alloy", *Materials and Design*, 30, **2009**, pp. 2237-2242.

[Kar10] R. Karthikeyan, V. Balasubramanian, "Predictions of the optimized friction stir spot welding process parameters for joining AA2024 aluminum alloy using RSM", *Int J Adv Manuf. Technol.* 51, **2010,** pp. 173–183.

[Kar10] R. Karthikeyan, V. Balasubramanian, "Predictions of the optimized friction stir spot welding parameters for joining AA2024 aluminum alloy using RSM", *Int J Adv Manuf Technol*, vol 51, **2010**, pp. 173-183.

[Kaw11] M. Kawasaki, "Processing of Ultrafine-Grained Materials through the Application of Severe Plastic Deformation", *Metall. Mater. Trans.* A, 42, **2011**, pp.3035.

[Lak07] A. K. Lakshminarayanan, V. Balasubramanian, K. Elangovan, "Effect of welding processes on tensile properties of AA6061 aluminium alloy joints", *Springer*, **2007**, pp. 286-296.

[Lan07] T. G. Langdon, "Ultrafine-Grained Materials: a Personal Perspective", *J. Mater. Res.*, 98, **2007**, pp. 251-254.

[Lan10] T. G. Langdon, "The impact of Bulk Nanostructured Materials in Modern Reasearch", *Rev. Adv. Mater*. Sci. Res., 25, **2010**, pp. 11-15.

[Mal15] B. Malard, F. De Geuser, A. Deschamps, "Microstructure distribution in an AA2050 T34 friction stir weld and its evolution during post-welding heat treatment", *Acta Materialia*, 101, **2015**, pp 90-100.

[Moh11] H. K. Mohammed, "comparative study between friction stir welding and metal inert gas welding of 2024 T4 aluminum alloy", *ARPN Journal of Engineering and Applied Sciences*, 6(11), **2011**, pp. 36-40.

[Mos14] M. Mosallaee, M. Dehghan, "Improvement of structural and mechanical properties of Al110 alloy via friction stir processing", *Journal of Materials Engineering and Performance*, 23, **2014**, pp. 3786-3793.

[Nad15] N. Nadammal, Satish.V. Kailas, J. Szpunar, Satyam Suwas, "Restoration mechanisms during friction stir processing of aluminium alloys", *Metallurgical and Materials Transactions* A, 46 A, **2015**, pp. 2823-2828.

[Nag16] H. D. Naghibi, M. Shakeri, M. Hosseinzadeh, "Neural Network and Genetic Algorithm Based Modeling and Optimization of Tensile Properties in FSW of AA 5052 to AISI 304 Dissimilar Joints", *Transactions of Indian Institute of Metals*, vol 69(4), *2016*, pp. 891-900.

[Orl09] D. Orlov, Y. Beygelzimer, V. Varyukhin, S. Synkov, N. Tsuji, and Z. Horita, "Microstructure evolution in pure AI processed with twist extrusion", *J. Mater. Process. Technol*., 50**, 2009**, pp. 96-100.

[Pra10] P. Prasanna, B. S. Rao, K. M. Rao, "Finite Element Modeling for Maximum temperature in friction stir welding and its validation", *Int J Adv Manuf Technol*, **2010**, pp. 2693-4.

[Pra17] R. S. S. Prasanth and K. Hans Raj, "Determination of optimal process parameters of friction stir welding to join dissimilar aluminum alloys using artificial bee colony algorithms", *Transactions of Indian Institute of Metals*, **2017**, pp. 1176-9.

[Rey03] A.P. Reynolds, W. Tang, T. Gnaupel-Herold, H. Prask, "Structure, properties, and residual stress of 304L stainless steel friction stir welds", *Scripta Materialia* 48, **2003**, pp.1289-1294.

[Sab13] I. Sabirov, M. Yu. Murashkin, and R. Z. Valiev, "Nanostructured aluminium alloys produced by severe plastic deformation: New horizons in development", *Mater. Sci. Eng*. A, 560, **2013**, pp. 1-24.

[Sah12] A. Sahai,., R. S. Sharma, , and K. Hansraj, "Mechanical properties of Al6061 processed by Equal Channel Angular Pressing", *Adv. Mater Res.*, 585, **2012**, pp. 392-396.

[Shi09] I. Shigematsu, Y. J. Kwon, N. Satio, "Dissimilar Friction Stir Welding for Tailor-Welded Blanks of Aluminum and Magnesium Alloys", *Material Transactions*, 50(1), **2009**, pp. 197-203.

[Sho14] M. H. Shojaeefard, M. Akbari, P. Asadi, "Multi Objective Optimization of Friction Stir Welding Parameters Using FEM and Neural Network", *International Journal Of Precision Engineering And Manufacturing*, vol. 15(11), **2014**, pp. 2351-2356.

[Sid16] H. Sidhar, N. Y. Martinez, R. S. Mishra and J. Silvanus, “Friction stir welding of Al-Mg-Li 1424 alloy”, *Materials and Design*, 106, **2016**, pp 146-152.

[Sil15] A. C. F. Silva, D. F. O. Braga, M. A. V. de Figueiredo, “Ultimate tensile strength optimization of different FSW aluminium alloy joints”, *Int J Adv Manuf Technol*, vol 79, **2015**, pp. 805-814.

[Ste01] W. Stephan Kallee, E. Deve Nicholas, W. M. Thomas, “Industrialization of Friction Stir Welding for Aerospace Structure, Structures and Technologies and Challenges for Future Launchers”, *Third European Conference, Strasbourg, France*, **2001.**

[Sur11] C. N. Suresha, B. M. Rajaprakash, S. Upadhya, “A study of the effect of tool pin profiles on tensile strength of welded joints produced using friction stir welding process”, *Materials and Manufacturing Processes*, vol 26(9), **2011**, pp.1111-1116.

[Ten09] I. N. Tansel, M. Demetgul, H. Okuyucu, A. Yapici, “Optimization of friction stir welding of aluminium alloy using genetically optimized neural network”, *Int J Adv Manuf Technol*, l. 48, **2009**, pp. 95-101.

[Tho03] W. M. Thomas, R. B. Dolby, “Friction stir welding developments, In S. A. David, T. Deb Roy, J. C. Lippold, H. B. Smartt, J. M. Vitek, editors, *6th Int. Trends in Welding Research*, **2003,** pp. 203–211.

[Tho91] W.M. Thomas, E.D. Nicholas, J.C. Needham, M.Gg Murch, Temple- P. Smith, C. J. Dawes, *G. B. Patent*, Application No. 9125978.8, **1991**.

[Ton17] A. Tongne, C. Desrayaud, M. Jahazi, E. Feulvarch, “On material flow in Friction stir welded Al alloys”. *Int J Adv Manuf Technol*, 239, **2017**, pp. 284-296.

[Val05] R. Z. Valiev, R. K. Islamgaliev, I. V. Alexandrov, “Bulk Nanostructured Materials from Severe Plastic Deformation”, *Prog. Mater. Sci.*, 45, **2005**, pp. 103–189.

[Val11] R. Z. Valiev, and T. G. Langdon, “Achieving Exceptional Grain Refinement through Severe Plastic Deformation: New Approaches for Improving the Processing Technology”, *Metall. Mater. Trans.* A, 42, **2011**, pp. 2942-2951.

[Zhi01] A. P. Zhilyaev, “Microhardness and microstructure evolution in pure nickel during high pressure torsion”, *Scr. Mater.*, 44**, 2001**, pp. 2753-2758.